The effect of air-borne ammoniumsulphate deposition on Pine forests.

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In the past, mainly at the beginning of this century, large parts of the heathland in Western Europe were planted with coniferous trees. Often used species are Scotch Pine (*Pinus sylvestris*) and Norway Spruce (*Picea abies*) and regionally also Corsican Pine (*Pinus nigra* var. *maritima*), Douglas Fir (*Pseudotsuga menziesii*), Sitka Spruce (*Picea sitchensis*), Giant Fir (*Abies grandis* Lindl.) etc.

In the Netherlands more than 60% of the present forests are situated on former heathland soils[1]. The condition of particularly coniferous forests is often poor[2]. A nation-wide investigation, carried out by the Dutch State Forest Service[2] in 1983, showed that 7 to 38% of all trees in Scotch Pine forests had less than one complete year-class of needles. In Douglas Fir forests 29 - 70% of the trees had less than 50% of the leaves considered normal for this climatic zone. 64% of the unhealthy Scotch Pine forests and 41% of the unhealthy Douglas Fir forests showed grey-green or yellow-green discoloured needles. A comparable investigation in 1984 showed a further decline with respect to 1983[1].

In Germany the vitality of the forests also decreases strongly. Air pollution is generally believed to be the main cause. Ulrich[3] ascribes the phenomena mainly to soil acidification as a result of acid or acidifying substances from the atmosphere. The high Al/Ca ratio, resulting from dissolution of aluminium by mineral acids and from leaching of calcium, is harmful to the root system.

Other authors[4], however, believe that the observed nutrient deficiencies and concomitant damage to the trees can be ascribed mainly to leaching as a result of ozone damage to the leaves. In the forests on former heathlands in the Netherlands, however, there is no correlation between the mean ozone concentration in the atmosphere and the forest condition[5, 1], but there is a clear correlation between the ammonia emission and the forest condition[6, 1].

Some authors mention a relation between intensive stockbreeding and the condition of Pine trees[7, 8]. Van Breemen et al.[9, 10] state that ammonia from manure reacts with sulphur dioxide from the atmosphere, causing wet and dry decomposition of large amounts of ammonium sulphate on trees and soil[11]. Nitrification of the ammonium[10, 12] caused a marked pH-decrease of the soil (temporarily down to pH 2.8).

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Whether deposition of ammonium on acidic forest soils will result in strong acidification depends on the type of forest and soil. Kriebitzsch[13], who conducted nitrification experiments in many types of acidic forest soils, divided them into four groups: A, B, C and D. In the soils belonging to group A there was no nitrification and ammonium was the only nitrogen source. In the soils belonging to groups B and C there was partial nitrification and in those belonging to group D there was total nitrification. The investigations in this study showed that heathland and *Pinus* soils mainly belong to group A. Field studies in the Netherlands in *Pinus nigra* and *Pseudotsuga menziesii* forests on former heathland soils showed indeed only partial or no nitrification. The nitrate levels were low, whereas the ammonium levels were high (table 1). The soils of healthy, moderately damaged and severely damaged forests had on an average a pH (H_2O) of 4.1, which indicates that in this type of forest soil the pH is determined by the nitrification limit. Analysis of precipitation in open plots and canopy throughfall in a *Pinus nigra* var. *maritima* forest in an area with intensive stockbreeding showed that NH_4^+ and SO_4^{2-} are quantitatively by far the most important ions[14] . In open plots SO_4^{2-} is fully compensated by NH_4^+, however, in canopy throughfall SO_4^{2-} is only partially compensated by NH_4^+ (tabel 2). Some authors mention foliar uptake of NH_4^+ [14, 15]

Ecophysiological experiments with needles of *Pinus nigra* var. *maritima* indeed showed uptake of ammonia, which was compensated by excretion of potassium, magnesium and calcium. Needle analyses in healthy and damaged *Pinus nigra* forests showed that premature shedding of the needles in damaged forests was related to K and/or Mg deficiencies in the needles[14]. As a result of the NH_4^+ uptake the nitrogen levels were significantly higher in the needles of damaged forests. Whether the observed cation excretion will result in disturbed nutrient budgets depends mainly on the soil condition. A high ammonium sulphate deposition leads to accumulation of NH_4^+ and leaching of K, Mg and Ca from the soil. Field investigations in *Pinus nigra* var. *maritima* and *Pseudotsuga menziesii* forests demonstrated that the NH_4^+ levels were significantly higher and the Mg and Ca levels significantly lower in soils of severely damaged forests (table 3). As a result the NH_4/K, NH_4/Mg and the Al/Ca

Table 1. pH and chemical composition of soil-distilled water extracts (1:3) of A: healthy, B: moderately damaged and C: severely damaged *Pinus nigra* and *Pseudotsuga menziesii* forests (μmol. kg^{-1} dry soil)

		pH(H_2O)			NH_4^+	NH_4^+(KCL)*	NO_3^-	K^+	Mg^{2+}	Ca^{2+}	Al^{3+}
	n	mean	min	max	mean	mean	mean	mean	mean	mean	mean
Pinus nigra											
A	20	4.1	3.5	4.6	334	687	271	137	77	153	191
B	16	4.0	3.4	4.9	384	751	130	47	45	128	158
C	20	4.1	3.7	4.4	509	1346	117	60	26	43	183
Pseudotsuga menziesii											
A	10	4.1	3.9	4.4	245	499	164	89	60	106	214
B	10	4.1	3.8	4.3	562	733	153	67	48	69	211
C	11	4.3	4.0	4.6	692	1240	157	67	22	36	211

* 0.5 M KCL extract

Table 2. The average chemical composition of precipitation in a: open plots and b: throughfall in a *Pinus nigra* forest in an area with intensive stock-breeding (μmol. l^{-1})

	NH_4^+	NO_3^-	K^+	Mg^{2+}	Ca^{2+}	SO_4^{2-}	Na^+	Cl^-	H^+
a	597	71	53	35	71	318	170	197	1.7
b	2283	147	196	94	150	1379	346	462	0.6

ratios increase. It is well-known that increased NH_4/K and NH_4/Mg ratios inhibit K^+ and Mg^{2+} uptake[16, 17, 18], while an increased Al/Ca ratio may damage the root system. Ulrich[3] mentions an Al/Ca ratio ≥ 5 in the soil solution as very critical for root damage. In both *Pseudotsuga menziesii* and *Pinus nigra* forests the NH_4/K and NH_4/Mg ratios are relatively low in healthy forests and significantly higher in damaged forests, while the average Al/Ca ratio is significantly higher in severely damaged forests and, particularly in *Pseudotsuga* forests, far above the critical value (table 3).

Apart from the premature shedding of needles as a result of nutrient deficiencies, the forests become more susceptible to secondary stress factors such as NH_3, O_3, drought and fungal diseases. In some regions of the Netherlands the condition of *Pinus nigra* and *Pinus sylvestris* rapidly decreases as a result of a certain fungal disease (*Diplodia pinea* (Desm.) Kickx). Needle analysis in infected and non-infected forests demonstrated that the nitrogen levels were significantly higher in *Diplodia* infected forests[14].

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Table 3. The ratios of some nutrients in soil extracts of A: healthy, B: moderately damaged and C: severely damaged *Pinus nigra* and *Pseudotsuga menziesii* forests (mol/mol)

		NH_4^+/K^+			NH_4^+/Mg^{2+}			Al^{3+}/Ca^{2+}		
	n	mean	min	max	mean	min	max	mean	min	max
Pinus nigra										
A	21	4.7	0.5	14.0	6.4	1.1	24.3	2.0	0.4	5.6
B	17	9.2	0.8	36.8	10.0	1.8	26.3	1.3	0.2	2.8
C	21	11.3	1.9	51.8	22.1	1.6	57.2	5.5	1.7	16.7
Pseudotsuga menziesii										
A	10	3.8	0.5	11.8	4.5	0.6	10.0	6.6	0.8	40.9
B	10	8.7	1.5	31.2	19.3	2.0	51.1	8.9	0.7	46.7
C	11	18.2	3.8	64.5	47.6	7.9	118.0	15.6	1.4	54.0

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